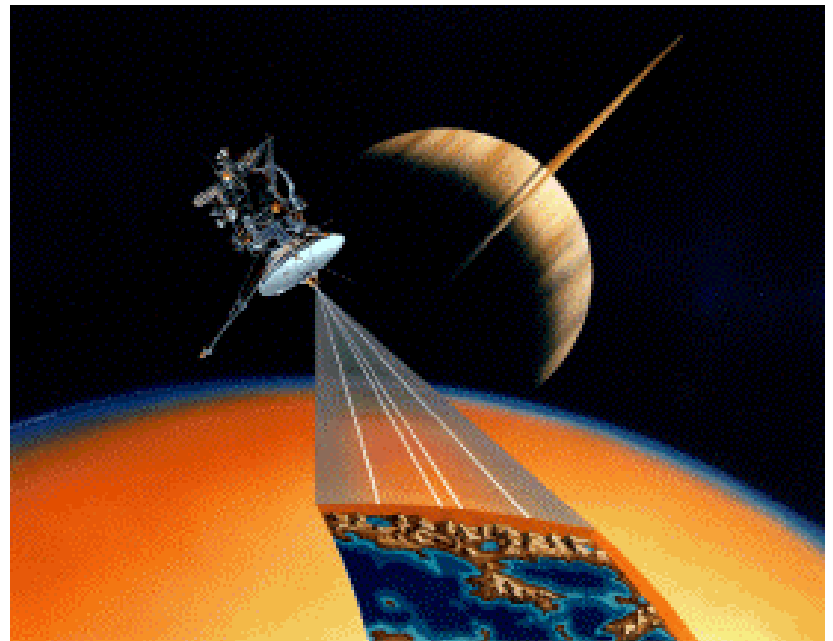


Thermal Control in Extreme Environments

Ram Manvi, Ph.D., P.E

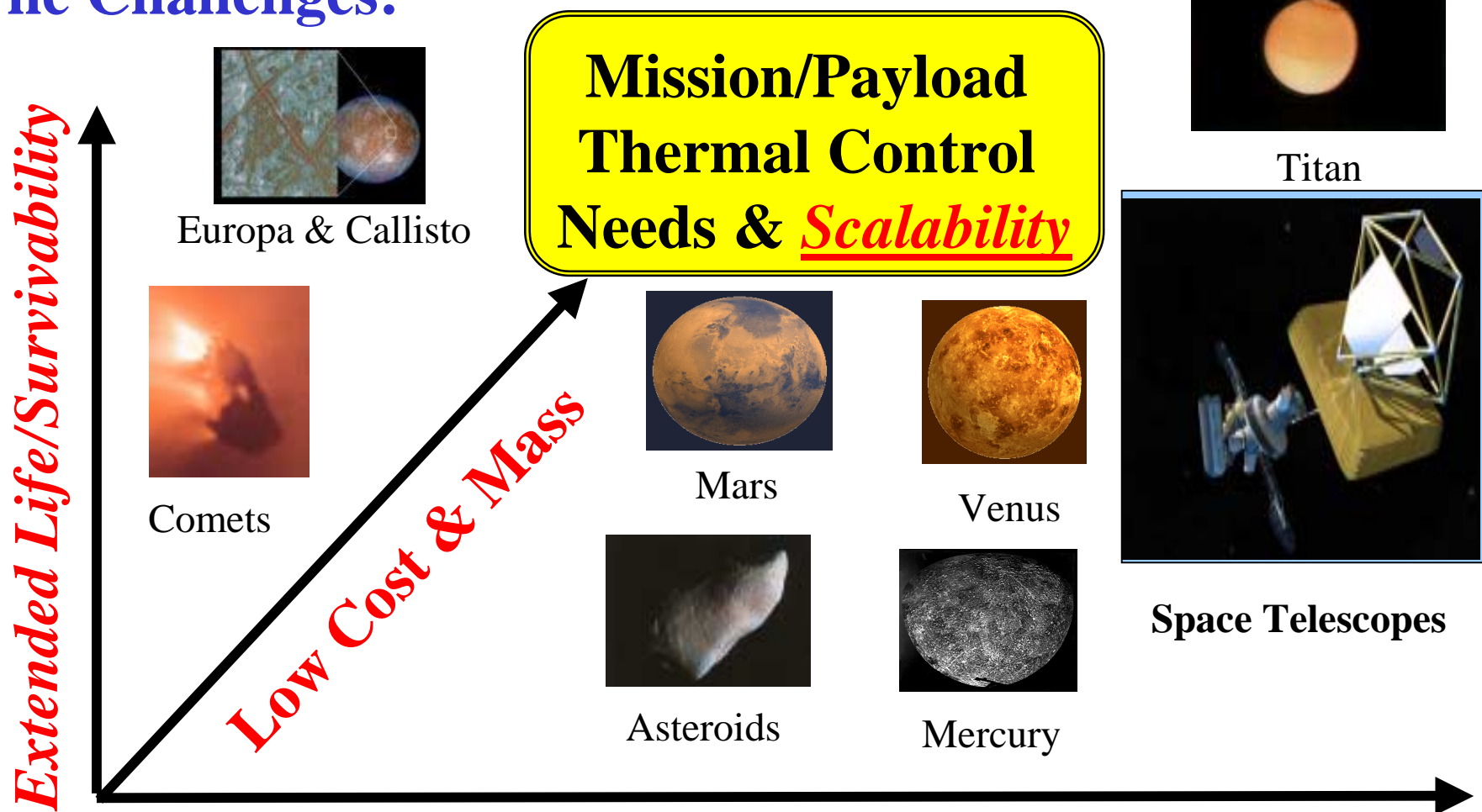
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May 16, 2003



Extreme Environments in Solar System Exploration

➤ The Challenges:



Environments: Thermal, Pressure, Chemical & Radiation

Mission/Payload Thermal Control Needs

- **Electronics-Power, Communications, & Control**
- **In-situ Science Measurements-Physical & Life**
- **In-situ Resources Production-Fuels, Food?**
- **Precursor Mission Infrastructure Establishment**
- **In-situ Mobility-Rovers & Robotics**
- **Aerobots, Ballutes, and Balloons**
- **Atmospheric Probes**
- **Aeroshells**

Goals of Spacecraft Thermal Control System

- **Maintain required equipment temperatures during entire mission**
- **Ensure safe and optimum performance during equipment operation**
- **Maintain specified temperature stability for delicate electronics, or stable optical components in sensors and instruments**
- **Satisfy specified temperature gradients of spacecraft equipment**
- **Maintain subsystem/ system Interface boundary temperatures**
- **Guarantee the correct operation of thermal control subsystem by means of control design, analysis, and conduct of tests**
- **Determine the most influencing factors, and manage them preferably by autonomous control by using available spacecraft resources and within Space environment constraints.**
- **To guarantee normal operation of equipment, thermal control must ensure that an item's temperature remains within predefined limits (specifications):**

An Example:

- *Temperature level- for instance: $-20^{\circ}\text{C} < T < +50^{\circ}\text{C}$*
- *Temperature stability over time- for instance: $dT/dt < 5^{\circ}\text{C}/\text{hour}$ Maximum*
- *Temperature gradients- for instance: $dT/dx < 0.5^{\circ}\text{C}/\text{cm}$ for an item of equipment*

Flight Operating Temperatures of Spacecraft Equipment

<u>Hardware Element</u>	<u>Operating Range (°C)</u>
➤ Telecommunications	-10 to +50
➤ Radar Units	-10 to +40
➤ On-board Computer	-10 to +50
➤ Batteries	-5 to +25
➤ Momentum & Reaction Wheels	-5 to +45
➤ Propellant Hardware	+7 to +65
➤ MLI	-160 to +250
➤ Heaters, Thermostats,& Heat Pipes	-35 to +60
➤ Pyrotechnics	-100 to +120
➤ Electric Motors	-45 to +80
➤ GPS Antenna	-95 to +70
➤ Power Control Units	-20 to +50
➤ Solar Arrays	-190 to +120

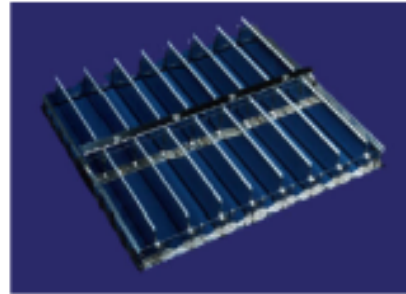
Typical Space Extreme Environments

Mission	Low Temp. °C	High Temp. °C	High Radiation Levels	High Pressure	Other Environmental Conditions
Venus Surface Exploration and Sample Return		460		90 Bar	Sulfuric acid clouds at 50 km 97% CO2 at the surface
Giant Planets Deep Probes	-180	380		100 Bar	
Comets Nucleus Sample Return	-140				Dust
Titan In-Situ	- 180			1.5 Bar	2-10% Methane Clouds Solid/liquid surface
Europa, Callisto Surface and Subsurface	-160		Europa 5 Mrad		
Aitken Basin Sample Return	-170				

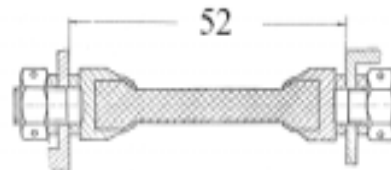
Typical Components of Spacecraft Thermal Systems

Passive Thermal Control

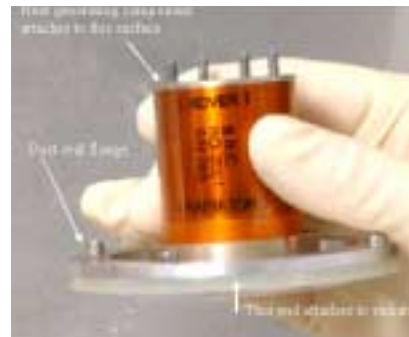
- Materials & Coatings: MLI, Paints, Silver Coated Teflon
- Optical Solar Reflectors (OSR)
- Space Radiators
- Cold Plates
- Heat Pipes
- Phase Change Materials
- Thermal Isolators



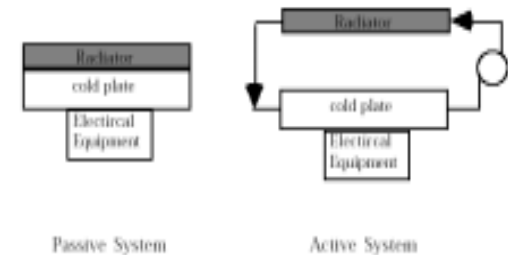
Louvers



Isolator Scheme of typical-low conductance standoff



Heat Switch

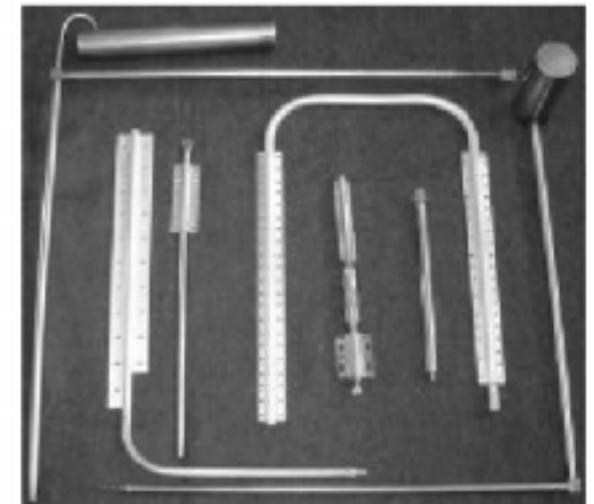


Passive System

Active System

Active Thermal Control

- Smart Coatings/Variable Emissivity
- Electric Heaters
- Thermostats
- Temperature Sensors
- Thermoelectric Coolers
- Expendable Cryogenics
- Active Refrigeration Systems
- Heat Switches
- Louvers



Heat Pipes Examples of heat pipes configurations made of metal fiber capillary structure and stainless steel shell

Titan In-Situ Exploration and Operation Environment

Avionics, Telecom, PMAD
and Instruments in
Thermally Controlled
Environment
 $\sim 0^{\circ}\text{C}$

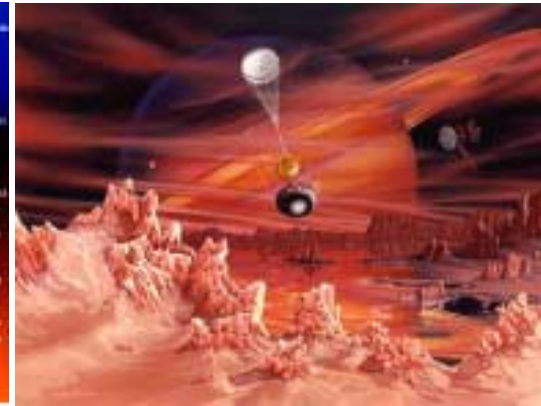
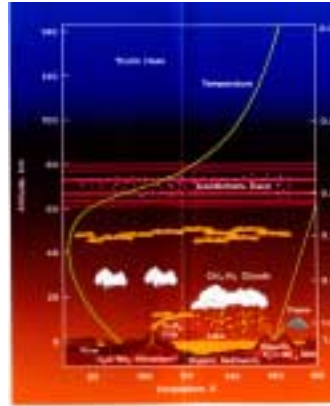
Minimize interface to
avoid potential thermal
and pressure leaks



Local thermal
control of sensors
and actuators using
waste heat of RPS



In-Situ Sensor



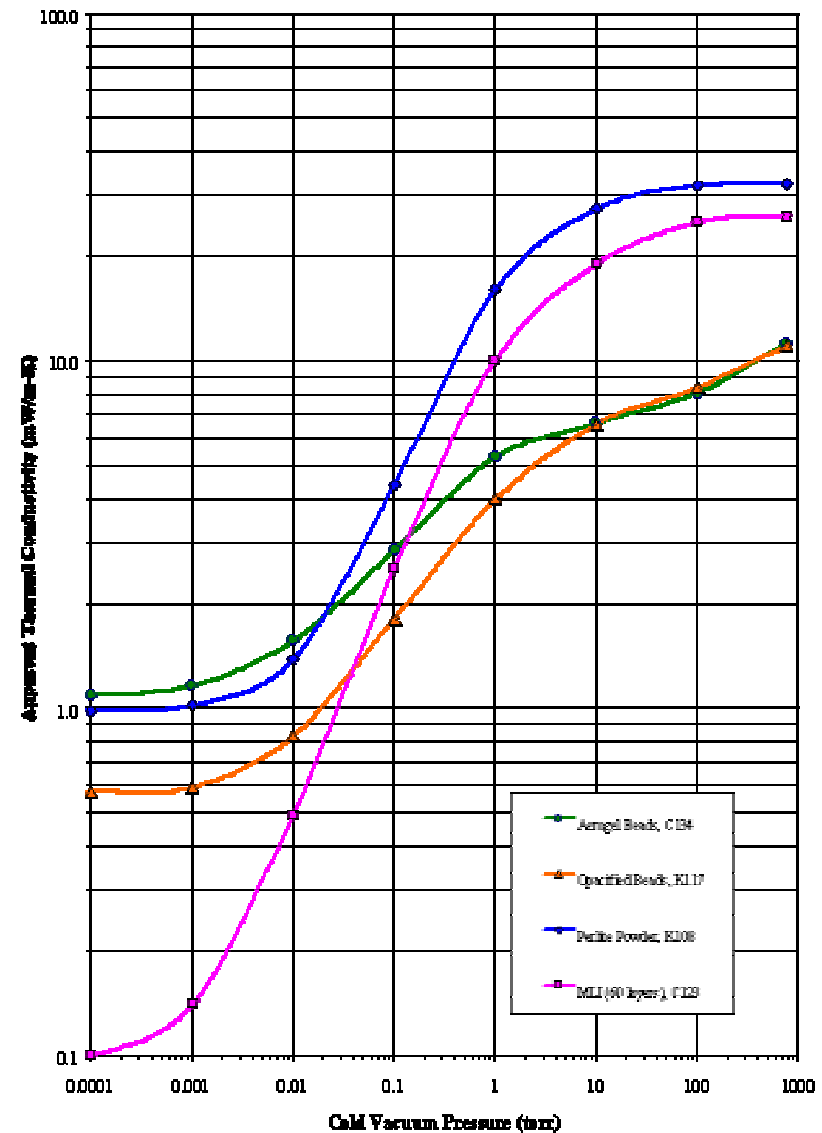
Components possibly exposed to Titan cold
temperature/pressure environment:

- Sample Handling and Transfer Mechanism
- HT Motor-Magnets
- Actuators and effector electronics
- Sensors
 - In-Situ science sensors
 - Fiber-optic bundles
- Sensor's interface electronics (LN preamplifiers)

The waste heat from RPS is used for keeping the thermal enclosure inside temperature above above 0°C . The external probes, mechanisms, and sensors are either kept above their survival temperatures by local thermal control using the RPS waste heat or have to survive the extreme cold

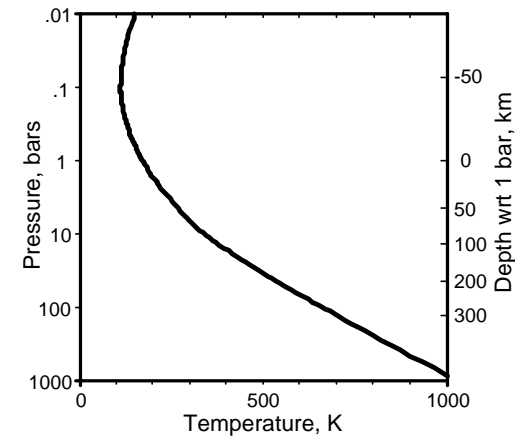
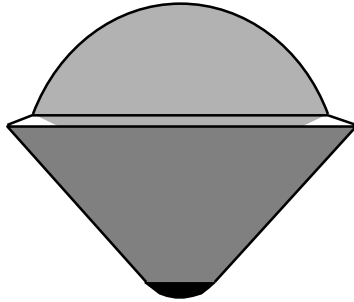
Cryogenic Insulation

Conventional insulation materials for cryogenic applications can be divided into three levels of thermal performance, in terms of apparent thermal conductivity. System k-values (mW/m-K) below 0.1 can be achieved for multi-layer insulation operating at a cold vacuum pressure (CVP) below 10^{-4} torr. For fiberglass or powder operating at a CVP below 10^{-3} torr, k-values of about 2 are achievable. For foam and other materials at ambient pressure, k-values around 30 are typical. A reasonable estimate for new composite insulation system is a k-value below 3 mW/m-K at a soft vacuum level (from 1 to 10 torr) and boundary temperatures between 80 K and 300K. Many combinations of radiation shields, spacers, and composite materials will be needed. System design considerations include installation, out-gassing, evacuation, compression, and end effects.



Jupiter Multi-Probe and Operation Environment

**Avionics, Telecom, PMAD
and Instruments in
Thermally Controlled
Environment
~ 50 C**



Components possibly exposed to Jupiter high temperature/pressure environment:

Sample Handling and Transfer Mechanism

HT Motor-Magnets

Actuators and effector electronics

Sensors

Temperature and Pressure

Fiber-optic bundles

Sensor's interface electronics (LN preamplifiers)

The inside temperature of the thermal control enclosure is kept below 50 C for several hours by using thermal energy storage and thermal insulation. The external probes, mechanisms, and sensors will use either local thermal control or have to survive the extreme hot environment

Thermal Control Technologies for Selected Missions

Mission	T/C Devices	Applicable Environment, K and bar	Comments
Venus Surface Exploration and Sample Return	<ul style="list-style-type: none"> • Thermal insulation • Thermal storage • Thermal Switches • Active cooling systems • Active refrigeration 	Over 730 K 0 to 70 bar	Missions lasting more than a few hours on surface will need RPS system
Giant Planets Deep Probes	Thermal insulation, PCM storage, thermal switches, heat pipes	160 to over 1000 K 0.1 to 100 bar	Temperature and pressure increase with depth in the atmosphere
Comets Nucleus Sample Return	<ul style="list-style-type: none"> • Thermal insulation • PCM thermal storage • Thermal switches, Heat pipes 	Generally cold, below 170 K No environment	
Titan In-Situ Explorer	<ul style="list-style-type: none"> • Thermal insulation • PCM thermal storage • Thermal switches, Heat pipes, active cooling loops 	80 to 160 K 0.1 to 1.5 bar	Long term operation on the surface requires RPS
Europa/Callisto Surface and Subsurface	Thermal insulation, thermal storage, active cooling loops	~ 120 K No Environment	Extreme Radiation on Europa

Decadal study missions need advanced thermal control to survive and operate in extreme temperature and pressure.

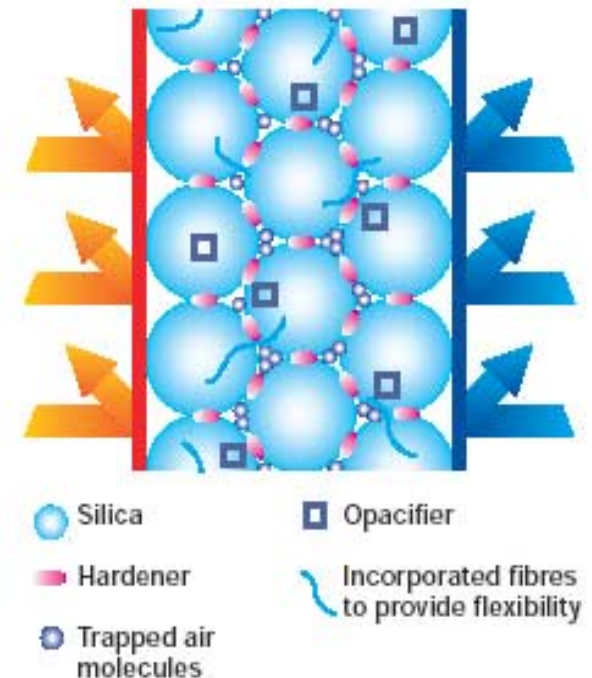
High-Temperature Insulation

High Temperature Insulation(HTI) will enable A number of ISRU processes such as Sabatier reactors, & Extraction of volatiles from regolith require high temperature operation (200 to 1000+ °C) for high efficiency and reduced mass, & volume reasons. High performance HTI will also be needed for Venus, and Jupiter Probe missions.

A concept for an extremely efficient insulating performance is due to an HTI material micro-porous molecular structure. The spherical fumed silica molecules are just in point contact with one another. This minimizes heat conduction through the solid. The interstices (micro-pores) between the silica particles trap air molecules and prevent them from transmitting heat by convection. The addition of infrared opacifiers in powder form minimizes heat transmission due to radiation.

Thermal conductivity (Standard pressure)

- At room temp : 0.019-0.021 (W/(m-K))
- At 200°C mean temperature: 0.023-0.025 (W/(m-K))
- At 600°C mean temperature: 0.034-0.041 (W/(m-K))
- Bulk density: (kg/m³) 140 - 800
- Service temperature range (°C) -190 - 1100



Technology Description:

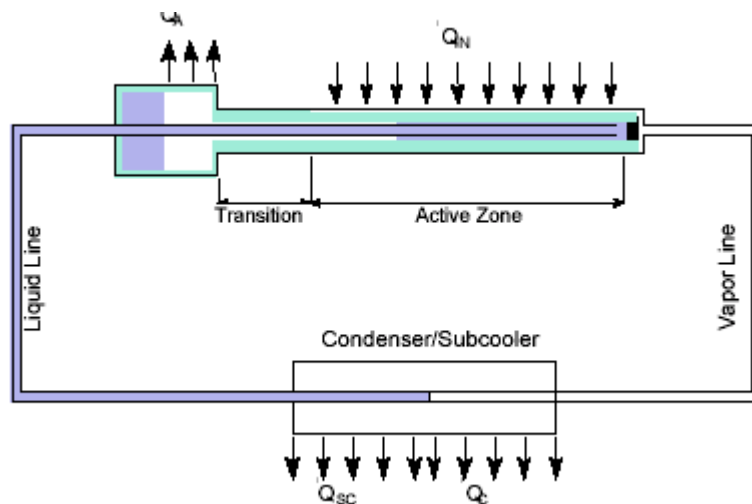
- Miniaturized two-phase heat transport device for thermal control.
- Passive heat transfer devices that rely on the pumping power of a wick; no moving parts or EMI.

Performance:

- Capable of heat loads ranging from 1 W to 10 W at temperatures ranging from -90 C to + 90 C
- Diode (shutdown) feature significantly reduces heater power requirements
- Tight temperature control (fractions of a degree)
- High reliability
- Evaporator size 6 mm OD, lines 1.6 mm OD
- Weight less than 150 grams

TRL:

- Current Technology is at TRL 2.



Miniature Loop Heat Pipe

R&D Issues

- This technology is very gravity sensitive.
- Justification based on zero-gravity effects on basic thermophysics of the process and liquid/vapor fluid management. Performance can be affected by reduced size, which does not scale linearly.

- CPL start- up (which includes pressure spike), boiling incipience, vapor (bubble) growth, porous media transient vapor and liquid flow.
- LHP hysteresis, miniaturization(scaling), nano devices complex geometries, high flux, conductance
- Scalability, super-capacity wicking structures for very large devices.

Two-Phase Thermal Loop

Technology Description (two variants):

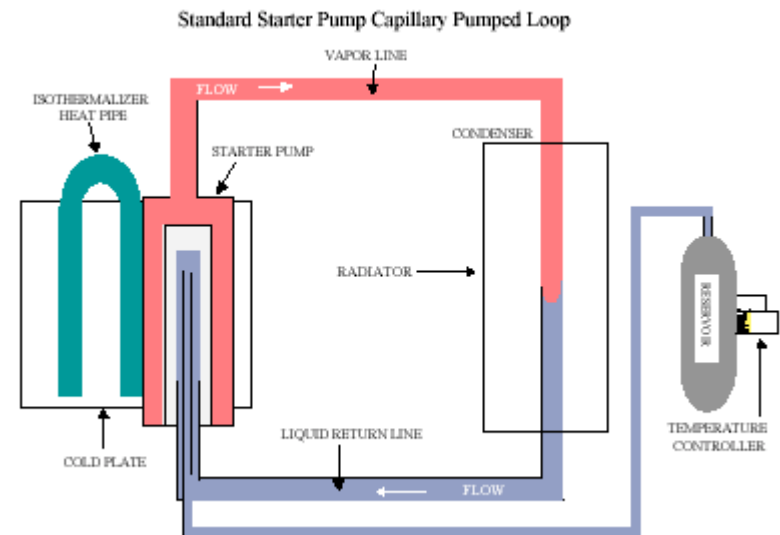
- 1) Cryogenic two-phase heat transport device for thermal control of sensors and/or optical benches, or 2) Multi-zone system for isothermalizing large areas
- Passive heat transfer devices that rely on the pumping power of a wick; no moving parts or EMI.

Performance:

- Capable of large (kW+) to small (mW) heat loads
- Transport over long distances (meters+) with very small temperature drops
- Tight temperature control (fractions of a degree)
- High reliability
- Isothermality over large areas

TRL:

- For $T < 75$ K, technology is at TRL3/4.



R&D Issues

- This technology is very gravity sensitive.
- Justification based on zero-gravity effects on basic thermophysics of the process. In particular, the liquid phase has start-up issues.

Non - Capillary Devices(Mechanical, Vapor, Electro-hydrodynamic)

Technology Description:

- Thermal control system driven by pressure generated by mechanical/electrical forces arising from application of a pump, compressor, or electric field to a dielectric working fluid
- Temperature ranges from ambient to $\sim 70\text{K}$ for Cryogenic applications
- System also applicable to high-temperature pumped loops for non-cryogenic applications for $\sim \text{kW}$ levels

Performance:

- Single Phase or Two-Phase System
- Heat Load up to hundreds of watts
- Meso-scale or micro-scale system
- Low Power consumption ($\sim 0.25\text{ W}$)
- Lightweight
- No moving parts
- Simple Feedback Control System w/ no time inertia
- Very low acoustic noise

TRL:

- TRL Level 4; Laboratory Breadboard Loop



Thermal Control Technology Status

Thermal Control Technology/Devices	State-of-the-Art	Needed for Future Missions	Comments
Phase Change Material thermal Storage	Paraffin waxes: 120 kJ/kg	1000 kJ/kg	Better packaging of PCM module Expendable PCM
Thermal Insulation	Open cell and batt insulation (under 100 °C)	Insulation to withstand high temp (>460 °C), lighter, compact	Inflatable insulation High temperature insulation
Thermal Switches	Wax heat switch, Loop heat pipes (under 100 °C)	High performance, high temperature operation	Need to look at thin film technologies for inflatables and balloons
Pressure vessel	Titanium vessel		Lighter
Active cooling	Mechanically pumped loop	Lighter and low power systems	Needed for both high and low temperature applications




Challenge: Present SOA thermal technologies are not able to protect electronics and mechanisms in extreme temperature and pressure environment expected in future missions

Extreme Temperature Thermal Technology Needs

Mission Environment	Thermal Technologies Needed	
	Passive	Active
<u>Hot Environment</u> Short duration missions (~1 h), Venus, Jupiter	High temp. Insulation, PCM, Thermal Switches, Pressure Vessels	Heat Pumps, Pumped Loop Radiators
<u>Hot Environment</u> Long duration missions (~days), Venus, Jupiter	Same as above	Active cooling loops, Active Refrigeration (RPS)
<u>Cold Environment:</u> Short duration missions (1-2 hours)(Titan, comets etc)	Low temp. insulation, PCM, thermal switches	Distributed Heat Sources/Pumped Liquid Loops
<u>Cold Environment:</u> Long duration missions (~days) (Titan, comets etc)	Same as above, heat pipes	Same as above +Active pumped cooling loops

A variety of passive and active thermal control technologies are needed to keep the electronics, mechanisms, and science equipment at their survival and operations temperatures. These technologies are needed for both the central thermal enclosure (Warm Box) and for local thermal control of hardware outside such an enclosure.

Key Products

	<u>Base (SOA)</u>	<u>Performance Needed</u>
 <p>Pressure Vessel</p>	<ul style="list-style-type: none"> • 100 kg/m³ for 100 atm e.g., Titanium tanks 	<ul style="list-style-type: none"> • 50 kg/m³ for 100 atm environment
 <p>Thermal Insulation</p>	<ul style="list-style-type: none"> • 1 W/mK at 500 °C and 1 atm and 200 kg/m³ bulk density, e.g., Aerogels, Perlite 	<ul style="list-style-type: none"> • 0.1 W/mK at 500 °C and 70 atm and bulk density of less than 50 kg/m³
	<ul style="list-style-type: none"> • 125 kJ/kg PCM thermal storage package 	<ul style="list-style-type: none"> • Thermal storage energy density of 300 to 1000 kJ/kg

Recommendations

- **Address Scaling Effects for a variety of Space Applications**
- **Address Autonomous & Intelligent/Smart Control of Thermal Systems**
- **Address Variable G Environments, & Incorporate Extreme Environments for Thermal Control considerations early in thermal design.**
- **Explore the extremes in fluid property variation ranging from cryogenic to liquid metals**
- **Enhance Miniaturization**
- **Address Extended Survivability of Thermal Control Hardware in Extreme Environments, Generate Data on Reliabilities, Failure Rates, & Redundant Hook Ups.**
- **Address On-board (Spacecraft) & On-surface (Exploration Hardware) Fluid Maintenance-Pumped Cryogenic & Heat Transport (Liquid, Solid/Liquid, Gas/Solid,etc.)**
- **Establish Applications of Phase change materials (solid- liquid) for transient energy thermal management, Energy Storage Needs, etc.**
- **Facilitate Enhanced Student participation in NASA research projects**
- **Establish Closer Collaboration between Universities, Government and Industry; Identify Joint research efforts on critical technologies**